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An Analysis of Runoff Ratios Across Urbanizing Gradients

Cole Jermyn

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by

Cole Jermyn
Candidate for Bachelor of Science
Environmental Resources Engineering
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APPROVED

Thesis Project Advisor: C N Kroll
Charles Kroll, Ph.D.

Second Reader: Stephen Shaw
Steve Shaw, Ph.D.

Honors Director: William M Shields
William M. Shields, Ph.D.

Date: 5/7/18

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Abstract

This study examines precipitation and streamflow patterns in watersheds in the Bronx, New York and Baltimore, Maryland to analyze runoff ratios, the ratio of runoff to precipitation, across varying levels of urbanization. i-Tree Hydro was also utilized to assess its effectiveness at modeling urban hydrology. NEXRAD precipitation data and USGS streamflow measurements were used to calculate monthly average runoff ratios for five watersheds of varying land cover characteristics. This data, supplemented by weather station data from BWI Airport, was also used to run the i-Tree Hydro model. Streamflow predictions from this model were used to calculate average monthly runoff ratios for comparison to the above estimates. Both the watershed-specific NEXRAD precipitation data and the BWI Airport precipitation data were used to calculate runoff ratios and run i-Tree Hydro. With both datasets, differences were shown between the runoff ratios of the watersheds with the greatest and least percentages of tree cover during summer months, indicating the importance of tree cover as a valuable resource for reducing runoff during high warmer months when evapotranspiration is high. This could be particularly valuable in cities susceptible to heavy precipitation in the summer months, such as Baltimore. At these sites, the i-Tree Hydro model was shown to take into account land cover, while underestimating the effect of seasonal changes on ET and subsequent runoff ratios.

Acknowledgements

Thanks to Dr. Charles Kroll (SUNY-ESF), Dr. Steve Shaw (SUNY-ESF), Charity Nyelele (SUNY-ESF), Brenden Covert (SUNY-ESF), Robert Coville (Davey Tree Expert Company), and Dr. Brianne Smith (CUNY-Brooklyn) for their assistance on this project. This research was supported by the United States Department of Agriculture (USDA) Forest Service with grant 16-DG-11132544-034 recommended by the National Urban and Community Forestry Advisory Council.

1.0 Background and Motivation

Trees play an often understated role in many processes in the urban environment, providing numerous ecosystem services along the way (Nowak & Crane, 2000). In urban environments, trees planted along sidewalks, in yards, and in parks help to clean the air, reduce the urban heat island effect, and mitigate stormwater runoff (EPA 2017). This project focuses on stormwater runoff and the related impacts of trees.

In many U.S. cities, the household effluent and the rainwater collected in storm drains are collected in one system known as a Combined Sewer System (CSS). Initially cheap to build due the lack of a necessity for separate pipe networks for stormwater and wastewater, these systems have become a challenge to manage in the era of environmental regulations. When heavy precipitation events occur within the sewershed, existing treatment facilities are unable to handle the excess flow, and a mixture of stormwater and wastewater is released, untreated, to waterways in what is known as a Combined Sewer Overflow (CSO). New York City, NY and Baltimore, MD, the two study areas for this project, both suffer from CSO events (NYC DEP, 2018; Baltimore City Department of Public Works, 2018).

Trees help to reduce the occurrence and magnitude of CSOs by slowing, storing, and evapotranspiring stormwater before it reaches the sewer system. Root systems physically slow stormwater as it infiltrates into soil, and take some of that water into the tree to be transpired through the stomata on the leaves. All of this helps to increase the time over which stormwater is introduced to the sewer system, decreasing the likelihood of CSO events (Gotsch, Draguljic & Williams, 2017). In addition, the transpiration process requires energy from the local environment, and thus provides cooling benefits which can alleviate urban heat island.

Because of this and the other benefits mentioned above, an accurate model of how these urban trees interact with the natural and built environments around them can be a valuable resource for city planners, arborists, and others to target areas for tree plantings and to justify greater investment in urban forestry. i-Tree is a software suite available from the USDA Forest Service to model these urban tree impacts (itreetools.org).

This project focused on i-Tree Hydro, a rainfall runoff model which represents the effects of urban trees on hydrologic processes (Wang et al., 2005, 2008; Yang et al., 2013). The initial goals of the project were to calibrate i-Tree Hydro for use on the Bronx River watershed and to assess the effectiveness of the model at estimating streamflow. Questions regarding i-Tree Hydro's ability to model critical urban hydrologic processes in the Bronx led to a second analysis in Baltimore, MD across a series of small headwater streams with varying land cover conditions across an urbanizing gradient.

2.0 Study Area 1: Bronx River Watershed

2.1 Motivation

The Bronx River served as the initial watershed used to calibrate i-Tree Hydro. This site was chosen because the Bronx is an initial study area for a USDA Nation Urban and Community Forest Advisory Council (NUCFAC) funded project "A New i-Tree Tool for Assessing Forest Impacts on Urban Ecosystems" that provided support for this research. The goal of this work was to develop a calibrated parameter dataset for i-Tree Hydro to the Bronx River. This dataset was then used by a SUNY ESF PhD student to run i-Tree Hydro at the census block level across the entire borough to assess the hydrologic service and benefits provided by trees in the Bronx.

2.2 Site Description and Available Data

The Bronx River is 24 miles in length, flowing from Westchester County to the East River in New York City (Figure 1). It has a watershed area of 38.4 square miles, an average temperature of 55°F and an average rainfall of 46 inches (117 cm). 12.7 square miles of the upper Bronx River watershed is diverted for municipal water supply (USGS, 2018). As part of the Million Trees NYC campaign, 280,000 trees were planted in the Bronx between 2007 and 2015 (Foderaro, 2015).

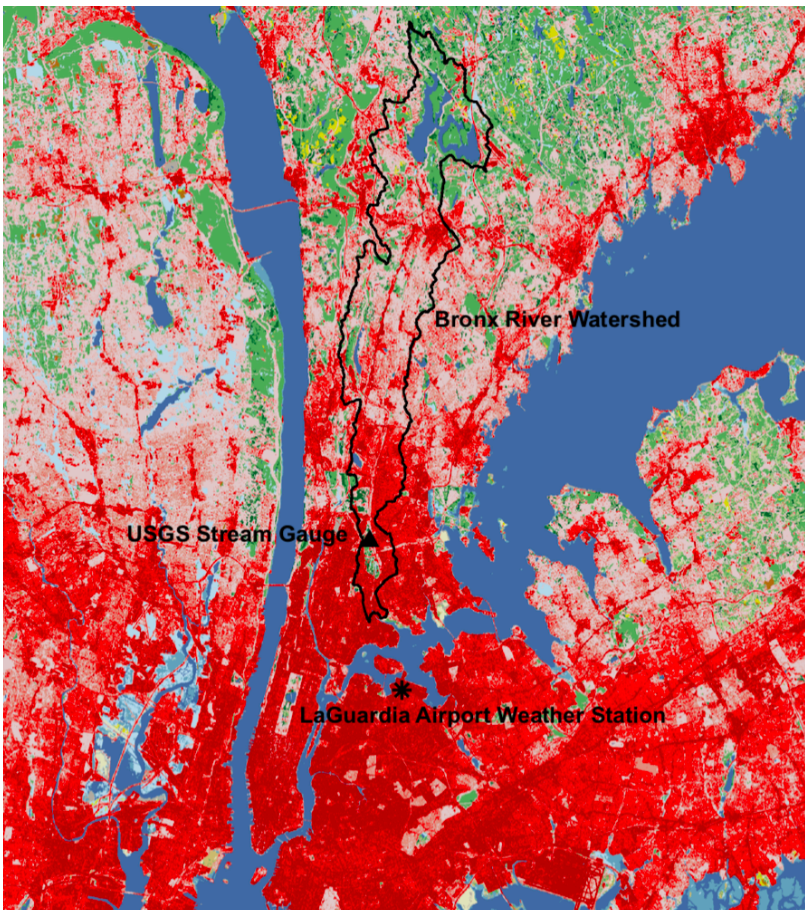

Figure 1. Map of Bronx River Watershed over NLCD 2011 dataset

Land cover used in the calibration was derived from classification of a 2011 one-meter digital orthoimage (USDA Farm Service Agency, 2011) of the Bronx River watershed into trees, short vegetation, bare soil, water and impervious cover using 250 training polygons and 250 assessment polygons; the overall classification accuracy across the assessment polygons was 94%.

Stream gauge data was taken from the United States Geologic Survey (USGS) gauge at the Bronx Botanical Gardens (Station Number 01302020), while weather data was taken from the Global Historical Climatology Network (GHCN) station at La Guardia Airport in Queens (Station ID USW00014732), which is located southeast of the watershed (Figure 1). The period of record for the USGS gauge is from October 1, 2007 to present, while for the GHCN station it is from October 7, 1939 to present.

2.3 Methodology and Output

To calibrate the model for the Bronx River Watershed, a number of scenarios were developed with varying input parameters. Table 1 contains an example of an input parameter dataset. The leaf area index (LAI) is the dimensionless ratio of the total area of leaves of a plant divided by the canopy area of the plant. Other parameters are self-explanatory.

Table 1. Input parameters for scenario 21 for Bronx River Watershed calibration

Parameter	Scenario 21
Average catchment tree leaf area index (LAI) in summer	7
Catchment Area (m^2)	9.967×10^7
Fraction of evergreen trees	0.0206
Fraction of evergreen shrub	0.0002
Percent Tree Cover	0.295
Fraction of connected impervious area (IA) of total IA	0.354
Fraction of impervious area without trees	0.5
Fraction of pervious area beneath trees	0.812
Fraction of impervious area beneath trees	0.188
Fraction of short vegetation in the catchment	0.1584
Fraction of bare soil	0.0426
Leaf on date of the year	62
Leaf off date of the year	338

These scenarios were then input into the i-Tree Hydro GUI's built-in calibration tool. The calibration was run over the timespan of January 1st, 2010 to December 31st, 2012, which coincides with when the land cover estimates were obtained. The calibration metric was to minimize the Nash Sutcliffe Efficiency of the real space weekly streamflows:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m{}^t - Q_o{}^t)^2}{\sum_{t=1}^{T}(Q_o{}^t - \overline{Q_0})^2} \quad (1)$$

where $Q_m{}^t$ is the modeled discharge summed for week t, $Q_o{}^t$ is the observed discharge summed for week t, and $\overline{Q_0}$ is the mean the T $Q_o{}^t$ values. Minimizing the NSE of weekly streamflows is equivalent to minimizing the mean squared error of weekly streamflows. As we are less concerned with matching peak streamflows than with capturing the overall water balance, a weekly calibration metric instead of a daily calibration metric was chosen. As previously mentioned, the stream gauge and weather data was obtained from the USGS gauge at the Bronx Botanical Gardens and the GHCN station at LaGuardia Airport, respectively. The results of these calibrations were a set of parameters (Table 2), which could then be used to run the model for the specific census block groups within the study area.

Table 2. Output parameters for scenario 21 for Bronx River Watershed calibration (denotes parameter calibrated in i-Tree Hydro)*

Output Parameter	Scenario 21
SimDayStart: starting simulation day	1/1/10
SimDayEnd: ending simulation day	12/30/12
TreeBarkLAI: Average LAI of tree bark in the catchment	1.7
ShrubBarkLAI: Average LAI of shrub bark (short vegetation) in the catchment	0.5
Alpha: time constant for surface flow*	64.4
Beta: time constant for surface flow*	38.8
PDS: Pervious Depression Storage*	0.674
LeafTransDays: length of leaf transition days	28
TreeSL: Specific leaf storage	0.2
ShortVegLAI: Average short vegetation LAI*	1.6
n: Scale parameter of power function*	2
m: Scale parameter of soil transmissivity*	0.116
T0(m^2): Soil Transmissivity at Saturation*	0.979
K0(m/h): Surface hydraulic conductivity*	0.140
WFS(m): Wetting front suction*	0.293
DWSMI(m): Wetted moisture content: Saturated soil moisture content - initial soil moisture content*	0.126
Volumetric Efficiency (NSE)	0.599

As shown above in Table 2, the NSE for this model calibration at a weekly timestep was 0.60, the highest of the scenarios tested. Figure 2 below shows a graph of predicted versus observed runoff for each month for the calibration period. Overall, the model's predicted runoff was 17% lower than the observed runoff during the time period. The peak seen in August, 2011 coincides with Hurricane Irene impacting the area. Outside of this month, it appears the model is consistently under-predicting runoff within the watershed, most likely due to an over-prediction of ET.

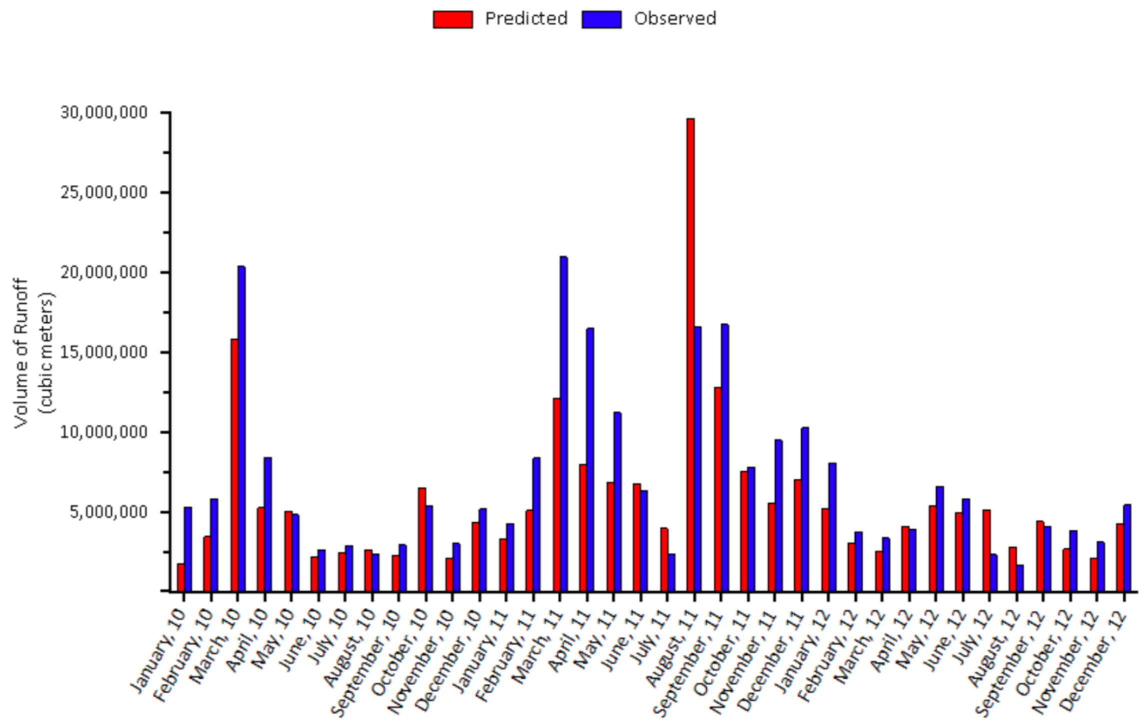

Figure 2. Monthly predicted and observed runoff from i-Tree Hydro scenario 21

2.4 Issues with Analysis

From these calibrations and the subsequent i-Tree Hydro model runs at census block groups within the Bronx, unanswered questions and potential issues were identified. The first issue was the accuracy of data. The closest reliable temperature and precipitation gauges were six miles from the stream gauge, outside of the watershed. The watershed itself is also large, at nearly 40 square miles, and affected by diversions and extensive stormwater infrastructure.

Second, it remained unclear if i-Tree Hydro worked properly to model the impact of trees and subsequent stormwater runoff. In i-Tree Hydro, some input variables are calibrated while others are set by the user (see Table 2). Our initial parameterization of the model produced large differences between predicted and observed streamflow series, and a number of different model parameterizations were done to produce a model that produced more accurate streamflow estimates (higher NSE). As such, it was not certain that the model represented flow series particularly well. There were also questions regarding whether the calibration routine which only allows minimization of hourly, daily or weekly real-space streamflows was the most appropriate method to capture tree impacts, as minimizing a real-space NSE generally steers the model to fit larger streamflows as opposed to capturing the overall water balance.

Finally, as seen in Figure 2 above, there appears to be a systematic under-prediction of runoff within the watershed, particularly during late winter and early spring. This bias may be the result of the model not effectively modeling the lack of ET capacity during these months or perhaps the model is improperly modeling urban snow dynamics.

New York City has limited streamflow gages to perform further data analyses to address these questions. We then sought another location that might be more suitable to test this model. This led us to a series of small watershed that part of the Baltimore Ecosystem Study.

3.0 Baltimore Ecosystem Study (BES)

3.1 The BES and Project Goals

The Baltimore Ecosystem Study (BES) is part of the Long-Term Ecological Research (LTER) Network established by the National Science Foundation. The LTER Network is a group of 28 sites in the U.S., Antarctica, and French Polynesia that span a wide array of ecological and anthropogenic conditions that serve as dedicated research sites (LTER, 2018). The BES is made up of Baltimore's city center, extending outwards to the suburbs and rural areas outside of the City of Baltimore. The BES was selected as a site for this portion of the project due to the prevalence of research and data already available for many of the watersheds within it. The average annual precipitation for the BES is 43 inches (109 cm), with average high temperatures ranging from 42°F in January to 89°F in July. The heaviest precipitation comes in the summer months, when convective thunderstorms are common and hurricanes and other tropical storms are more prevalent (BES, 2018).

The goals for this portion of the project were to:

- Calculate a temporal series of runoff ratios, the dimensionless ratio of streamflow (runoff) volume to precipitation volume, for a series of watersheds with varying land cover within the BES.
- Examine the relationships between runoff ratios and land cover characteristics in these watersheds.
- Estimate runoff ratios using i-Tree Hydro at a subset of these watershed and to compare these estimates to the calculated runoff ratios.
- Reflect on the above analyses and address some of the i-Tree Hydro issues identified in Section 2 of this honors thesis.

3.2 BES Subwatersheds

Nine watersheds were identified within the BES for use in this portion of the project. These nine watersheds were first identified by Smith et al. (2013) for their similar watershed areas and average basin slopes, but varying land cover. To minimize time devoted to i-Tree Hydro's lengthy calibration routine, five of the watersheds were selected from this list for model runs (specified below). These watersheds were selected for their availability of streamflow data, and the wide variety of land cover characteristics they exhibited (Figure 3 and Table 3).

Table 3. Watershed characteristics of nine study watersheds (* denotes watershed selected for i-Tree Hydro model run)

Watershed	Area (mi^2)	USGS Gauge Number	Impervious Fraction
Baisman Run*	1.47	1583580	0.037
Cranberry Branch	3.29	1585500	0.112
Upper Gwynn's Falls*	4.23	1589197	0.281
Minebank Run	2.06	158397967	0.299
Herring Run*	2.13	1585200	0.321
Whitemarsh Run	2.73	1585090	0.376
Moores Run	3.52	1585230	0.398
Herbert Run*	2.47	1589100	0.451
Dead Run*	5.52	1589330	0.522

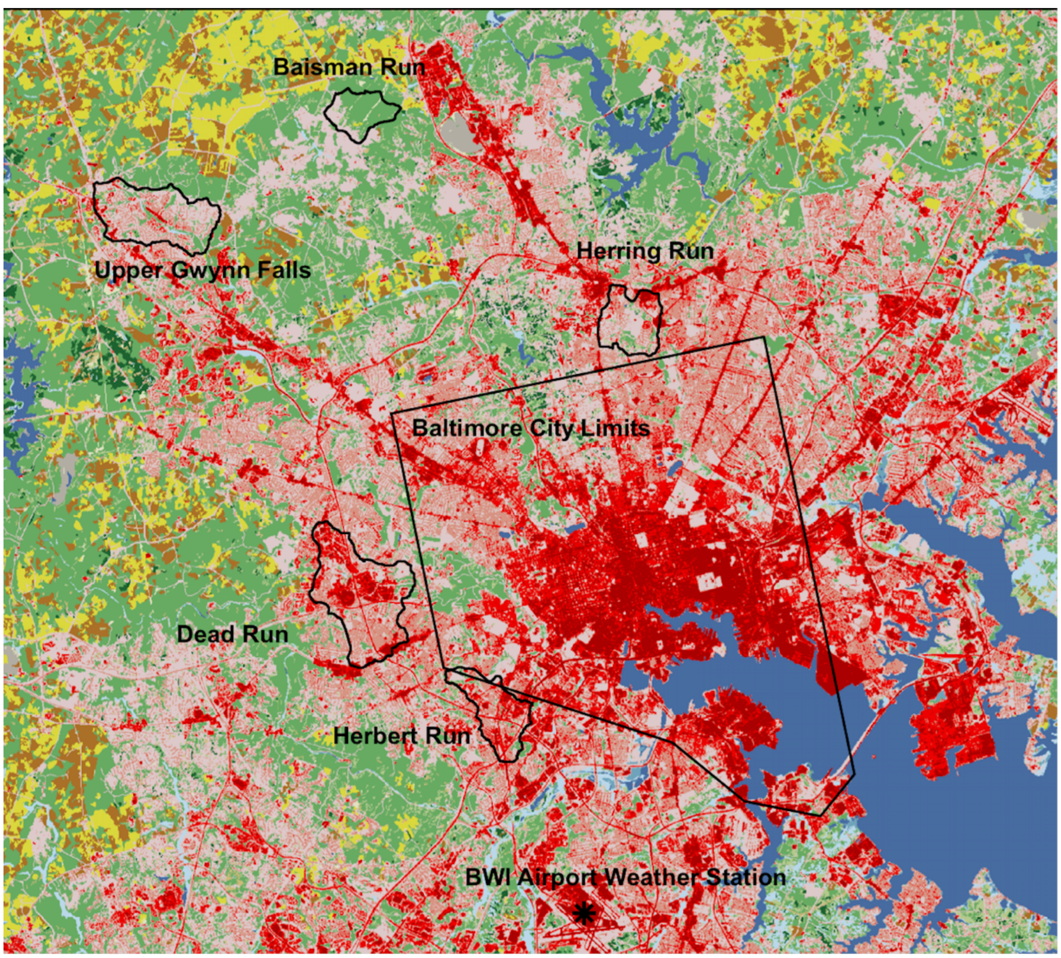

Figure 3. Modeled watersheds with NLCD 2011 data

3.3 Methodology

3.3.1 Runoff Ratios

To construct the average monthly runoff ratios for each of the nine watersheds, daily average streamflows were obtained from the USGS National Water Information System (NWIS) for each watershed for the timespan January 1st, 2000 to December 31st, 2009. Precipitation data was provided by Dr. Brianne Smith from the Earth and Environmental Sciences Department at Brooklyn College (Smith et al., 2013) in the form of 15-minute, bias-correct NEXRAD data, averaged across the watershed for each of the nine watersheds. Calculating monthly runoff ratios makes an implicit assumption of little change in storage in the watershed over a month, which generally is not valid given season groundwater, surface water and soil moisture storage variations. This can produce unusual results, especially in months with little precipitation. Regardless, for this initial analysis, monthly runoff ratios were calculated using recorded precipitation and streamflow during the month.

This data was processed using R statistical software. Any missing data points at the 15-minute timestep were assumed to be zero precipitation, and thus were disregarded when the data was aggregated to an hourly timestep. This hourly data was then compared to the hourly precipitation data from the NCDC weather station at BWI Airport, which is located approximately 5 miles south of the City of Baltimore. For hours where there was no NEXRAD data, the hourly precipitation at BWI Airport was used.

The impetus behind using the NEXRAD precipitation data was that it would provide a more local and hopefully more accurate precipitation dataset than the BWI airport data for use in calculating the runoff ratios and the i-Tree Hydro model runs. However, anomalous data points within the NEXRAD data led to questions regarding the accuracy of this data.

Figure 2 below shows the relationship between the NEXRAD precipitation data and the BWI precipitation data at the at the Herbert Run watershed for both hourly and daily precipitation data. Herbert Run is the nearest of the five watersheds to BWI Airport, so it was expected that these datasets would show the strongest correlation. However, at an hourly level, there is very little relationship between this data, though at a daily level, there is a stronger relationship.

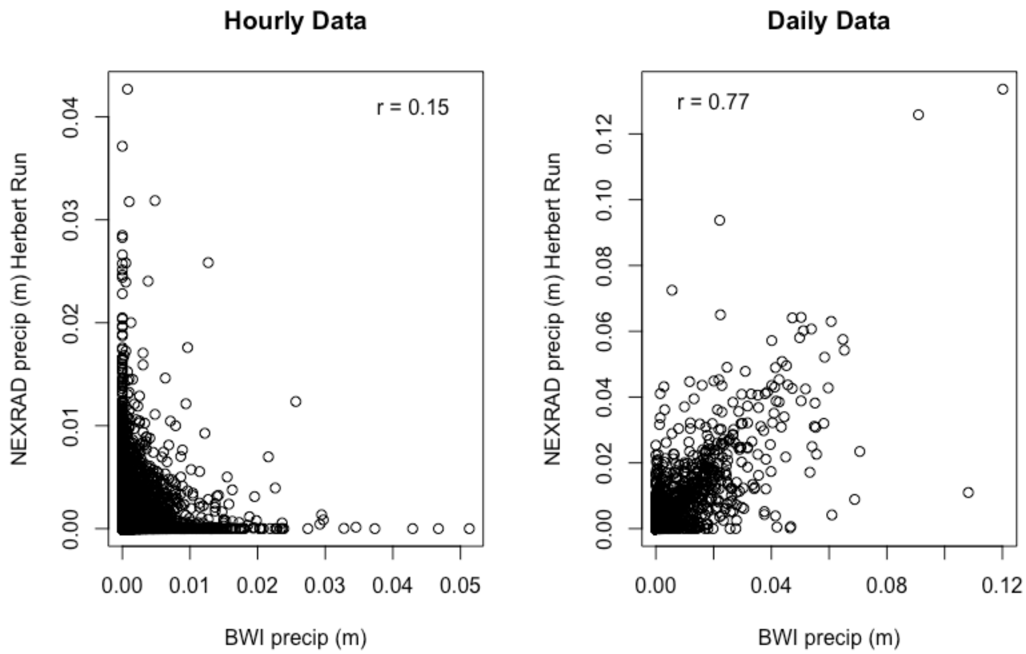

Figure 4. NEXRAD precipitation in the Herbert Run watershed compared with that at BWI Airport, at an hourly and daily timestep. Herbert Run is the nearest watershed to the BWI station and should be best represented by that data.

Monthly average runoff ratios were then calculated for total precipitation (depth) and stream discharge normalized by drainage area (depth) for the timespan January 2000 through December 2009. Due to uncertainty regarding the NEXRAD data, runoff ratios were calculated using this adjusted NEXRAD data (Figure 6 below and Table 5) and with the BWI Airport data (Figure 7 below and Table 6 in appendix). Note that the i-Tree Hydro model is most commonly run using data from the nearest NWS meteorological station, which in this case would be BWI Airport for all of these watersheds.

3.3.2 Land Cover Classification

Land cover classifications for the nine watersheds were completed by Charity Nyelele, a PhD student at SUNY ESF who is involved with the NUCFAC project. Watersheds were delineated using USGS StreamStats. Tree, short vegetation, bare soil, water and impervious cover percentages were obtained from a 3.2ft Urban Tree Canopy (UTC) land cover dataset obtained from the USDA Forest Service's UTC assessment (O'Neil-Dunne, 2018). Directly Connected Impervious Area (DCIA), an input to i-Tree Hydro, was calculated using the Sutherland equation within i-Tree Hydro (Sutherland, 2000).

For the fraction of trees over pervious area, fraction of trees over impervious area, fraction of short vegetation in the catchment, fraction of bare soil, fraction of evergreen trees and fraction of evergreen shrub (short vegetation), the original values based on image classification and the National Land Cover Database data were used and adjusted proportionally based on the land cover percentages in each watershed. The results of these classifications can be seen below in Table 4 for the five subwatersheds at which we will run i-Tree Hydro. Figure 5 contains plots of the overall runoff ratios for the entire 10-year time period versus fraction of tree cover and fraction of impervious surface. As expected, there is a general pattern where runoff ratios decrease with increasing tree cover and increase with increasing impervious surface. The one usual data point is for Upper Gwynn's Falls, which has the largest fraction of short vegetation, which would generally decrease runoff ratios.

Table 3. Land cover fractions for five target watersheds

Land Cover Type	Baisman Run	Upper Gwynn's Falls	Herring Run	Herbert Run	Dead Run
Trees	0.799	0.418	0.437	0.328	0.277
Short Vegetation	0.163	0.300	0.237	0.213	0.197
Impervious Cover	0.037	0.281	0.321	0.451	0.522
Water	0.000	0.000	0.002	0.004	0.002
Bare Soil	0.000	0.001	0.002	0.004	0.001
Tree over Impervious	0.073	0.038	0.040	0.030	0.025
Tree over pervious	0.725	0.380	0.397	0.298	0.252
Evergreen Tree	0.000	0.015	0.024	0.043	0.000
Evergreen Shrub	0.005	0.009	0.000	0.000	0.001

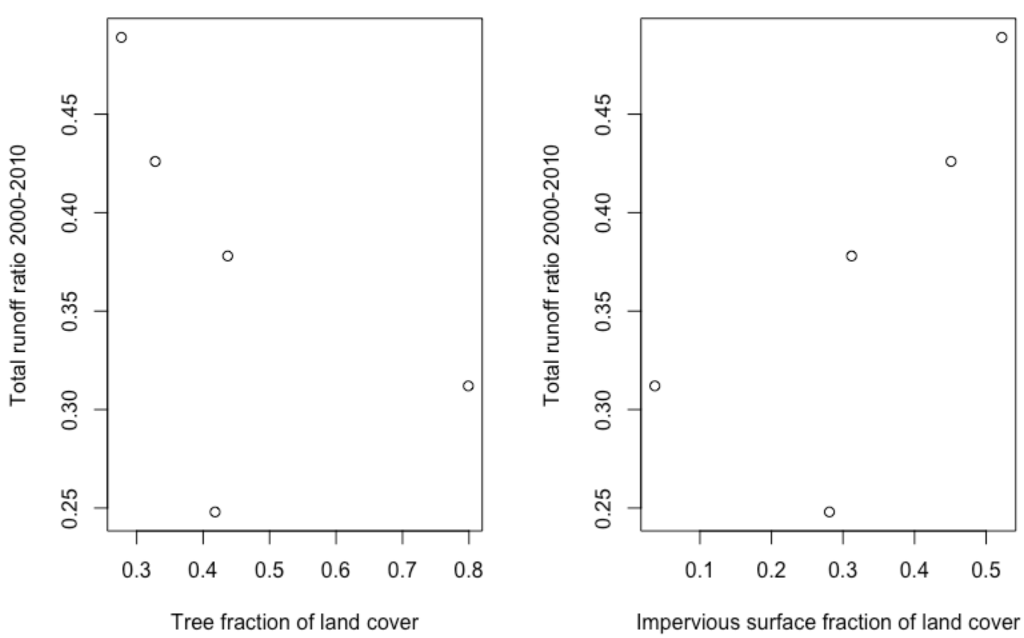

Figure 5. Total runoff ratios for five target watersheds as a function of tree cover and impervious cover

3.3.3 i-Tree Hydro Methodology

i-Tree Hydro Version 6 was used for all model runs for the BES portion of this project. An older version of i-Tree Hydro was applied to one of our Baltimore study sites (Dead Run) for a for three short storm events in 2000 (Wang, Endreny & Nowak, 2008). To use the adjusted NEXRAD precipitation data for running i-Tree Hydro, a raw weather file of hourly data at BWI Airport was first downloaded from the National Climate Data Center. After R preprocessing to remove repeated data points, this file was processed using the built-in weather processor in i-Tree Hydro. The processed weather file was then downloaded, and the adjusted NEXRAD precipitation data for each of the five study watersheds was used to replace the existing precipitation data within the weather file. To run i-Tree Hydro with the BWI Airport precipitation data, the original raw weather file from BWI was used. Streamflow data was downloaded from the USGS NWIS at a 15-minute timestep for each watershed. Topographical Index (TI) files, which indicate the propensity for surface saturation across the landscape and are an i-Tree Hydro input, were created using the i-Tree Hydro GUI for each watershed.

The model was calibrated for each watershed over the timespan of January 1st, 2007 to December 30th, 2009. As in the Bronx, the model was calibrated to maximize the real space NSE of the weekly streamflows. Using the parameters obtained from this calibration, the model was then run over the full time span of January 1st, 2000 to December 30th, 2009. This process was completed for each of the five study watersheds. Extended outputs from the model runs were stored for further analysis.

3.4 Results

3.4.1 Runoff Ratios

Figure 6 below shows the monthly average runoff ratios, calculated using the USGS streamflow measurements for each watershed and the adjusted NEXRAD precipitation data. These runoff ratios were calculated using the BWI Airport precipitation data as well (Figure 7). These results demonstrate the same general trends as the runoff ratios calculated using the NEXRAD data. There were two main takeaways from these results.

First, both of these datasets exhibit a strong seasonal variation in runoff ratios as is expected, where runoff ratios peak in the winter and early spring months, when evapotranspiration (ET) is low, and reach their lowest point in the late summer when ET is at its peak. This matches previous expectations for seasonal effects on runoff ratios.

Second, the comparison of runoff ratios between the watersheds for the most part matches expectations. There are high runoff ratios across the watersheds in the winter months, when ET is at its nadir. During the summer months, the most forested watersheds — Baisman Run and Upper Gwynn's Falls — have the lowest runoff ratios and therefore the highest expected ET. Contrary to this, the most urbanized watersheds — Dead Run and Herbert Run — have the highest runoff ratios. It is unclear why Baisman Run has the highest runoff ratio in February and March; this may be due to snow melt within this watershed.

The lower runoff ratios of Baisman Run and Upper Gwynn's Falls during the summer months are also important given these months experience the greatest frequency of thunderstorms and other heavy precipitation events. Having adequate forest cover within a watershed may be an important factor in decreasing flood risk during these high-intensity, shortduration storm events. The runoff ratios are also closer together during the winter months, when precipitation events are likely to be larger frontal systems rather than the smaller thunderstorms of the summer.

One outlier removed from the BWI Airport data was the runoff ratio of each watershed in October of 2000. This month had monthly runoff ratios of 2.5 at Dead Run to 7.1 at Baisman Run. This is due to only 2 mm of precipitation being measured at the BWI Airport station over the month, while streamflow values were not equally low. This is the major limitation of calculating runoff ratios at a monthly time step which ignores watershed storage. During low precipitation months, one would expect reduction in groundwater storage as this storage continues to supply water to the stream. This removed data point is reflected in Figure 7 and Table 6 (in Appendix).

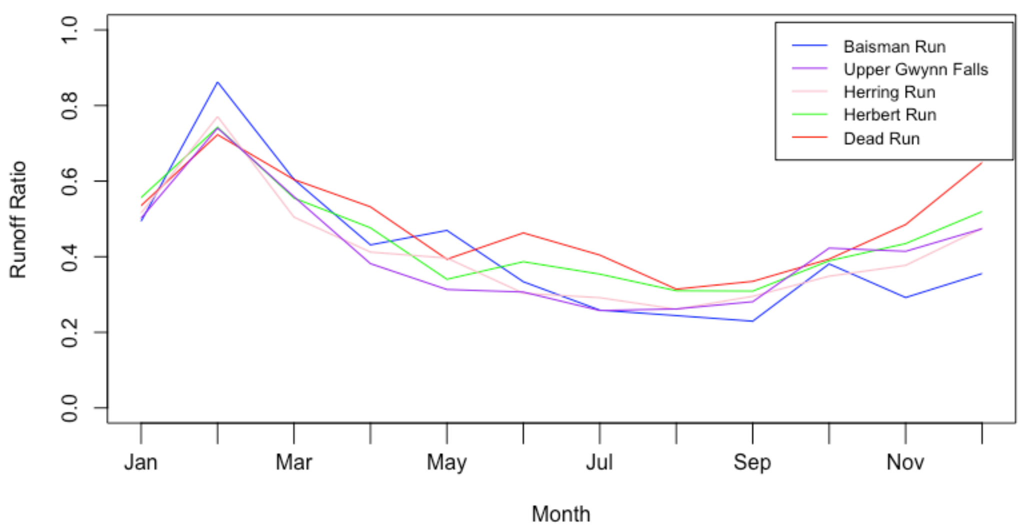

Figure 6. Average monthly runoff ratios (2000-2009) using observed streamflow and adjusted NEXRAD precipitation data

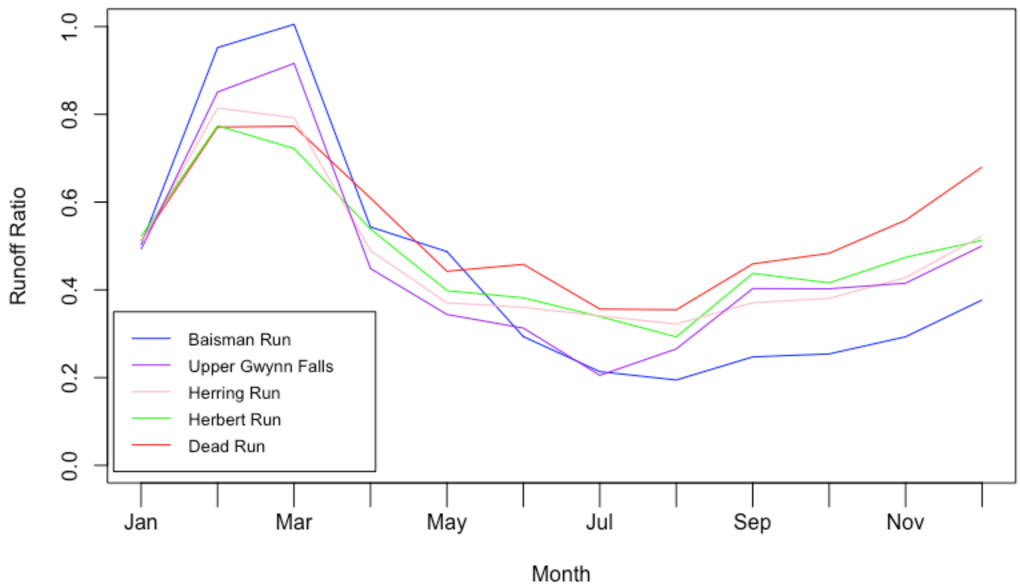

Figure 7. Average monthly runoff ratios (2000-2009) using observed streamflow and BWI Airport precipitation

3.4.2 i-Tree Hydro Output

The NSE from i-Tree Hydro prediction of weekly streamflows over the calibration period (January 2007 to December 2009) ranged from -0.21 at Baisman Run to 0.46 at Dead Run, and over the validation period (January 2000 to December 2006) the NSE ranged from -0.11 at Baisman Run to 0.43 at Dead Run. The full results for NSE using both the BWI Airport and NEXRAD precipitation can be seen below in

Table 4. These values are from i-Tree Hydro runs using both the NEXRAD and the BWI Airport precipitation data. From this data, it is clear that i-Tree Hydro is more effectively modeling the hydrologic cycle in the most-urbanized watersheds such as Dead Run, while less effectively modeling the most-forested watersheds (Baisman Run, Upper Gwynn's Falls). Unexpectedly, some of the NSE values are higher for the validation period than the calibration period, though in general these values are similar. Also, both Herbert Run and Herring run showed lower NSE values with NEXRAD precipitation than with the BWI precipitation for the validation period. Figure 12. Monthly predicted and observed runoff for Dead Run watershed for calibration period (January 2007 - December 2009)

Table 9 in the appendix shows the parameter set after calibration for each of the five target watersheds. Even at Dead Run , where the model calibration and validation produced the highest NSE, the model generally underestimates ET in the late summer and early fall (see Figure 12 of appendix). This result suggests that the ET dynamics of this model should be more thoroughly investigated.

Table 4. Weekly Nash Sutcliffe Efficiency during Calibration and Validation phase using BWI Airport data

Model Period	Baisman Run	Upper Gwynn Falls	Herring Run	Herbert Run	Dead Run
BWI Calibration	-0.211	0.026	0.317	-0.182	0.466
BWI Validation	-0.107	0.093	0.265	0.308	0.425
NEXRAD Calibration	0.329	0.478	0.350	-0.158	0.622
NEXRAD Validation	-0.002	0.21	-0.34	0.213	0.500

Figure 8 and Figure 9 below show the average monthly runoff ratios calculated using i-Tree Hydro modeled streamflows with the adjusted NEXRAD precipitation data and the BWI data, respectively. The most apparent feature of Figure 7 is the extreme scale and variation in runoff ratios modeled for the Baisman Run watershed as compared to the others. This is the result of the model significantly over-predicting the transmissivity at saturation of the soils within this watershed by a factor of 1100 times as compared to that value for the BWI Airport precipitation model runs. This most likely is an issue with the model calibration. For all models, the calibration routine started at default parameter values and was allowed to calibrate automatically to maximize the real-space NSE of weekly streamflows. Further exploration of the calibration routine and the solution space is warranted, as this routine may have identified a local as opposed to a global optimal solution. This also could be the result of the model being developed for use on urban watersheds, rather than the 80% forest cover of Baisman Run. Furthermore, i-Tree Hydro does not calibrate LAI as part of the calibration routine, including it instead as a user input. LAI is used to calculate stomatal resistance in the modified Penman-Monteith equation (Shuttleworth, 2013) which is used to calculate potential ET from trees (Hirabayashi & Endreny, 2016). Because LAI has a direct effect on ET rates, the model's inability to adjust this metric may be a factor in the lack of seasonal effects of ET in the model output. Because of Dead Run's low fraction of tree cover, it may experience the smallest effects from this lack of LAI calibration. In addition, ET from trees is calculated from the potential ET as a linear function of available soil moisture (Wang, Endreny & Nowak, 2008). This simple approach may not capture ET dynamics in an urban catchment.

Despite this, it can be seen that the effect of urbanization and impervious surfaces is being represented in the model to some degree, as both figures show greater runoff ratios in Dead Run and Herbert Run, and the lowest in Herring Run and Upper Gwynn's Falls.

However, these model outputs do not show the same seasonal variation in runoff ratios as the measured values in Figure 6 and Figure 7 above. This may indicate that i-Tree Hydro is not adequately taking in to account the effect of season variation in ET patterns across watersheds of different levels of forest cover. Figure 10 below shows the relationship between measured runoff ratios and i-Tree Hydro modeled runoff ratios for each watershed. Rather than following the 45° line that would show a direct correlation between the observed and predicted runoff ratios, there seems to be little in the way of a relationship between the two series.

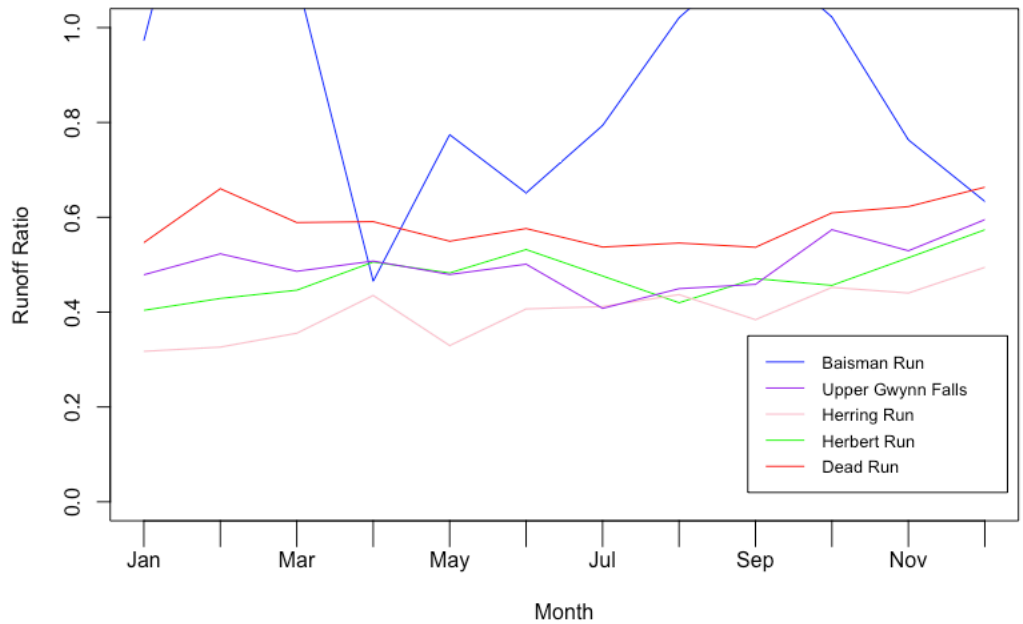

Figure 8. Average monthly runoff ratios (2000-2009) using i-Tree Hydro streamflow predictions and adjusted NEXRAD precipitation data

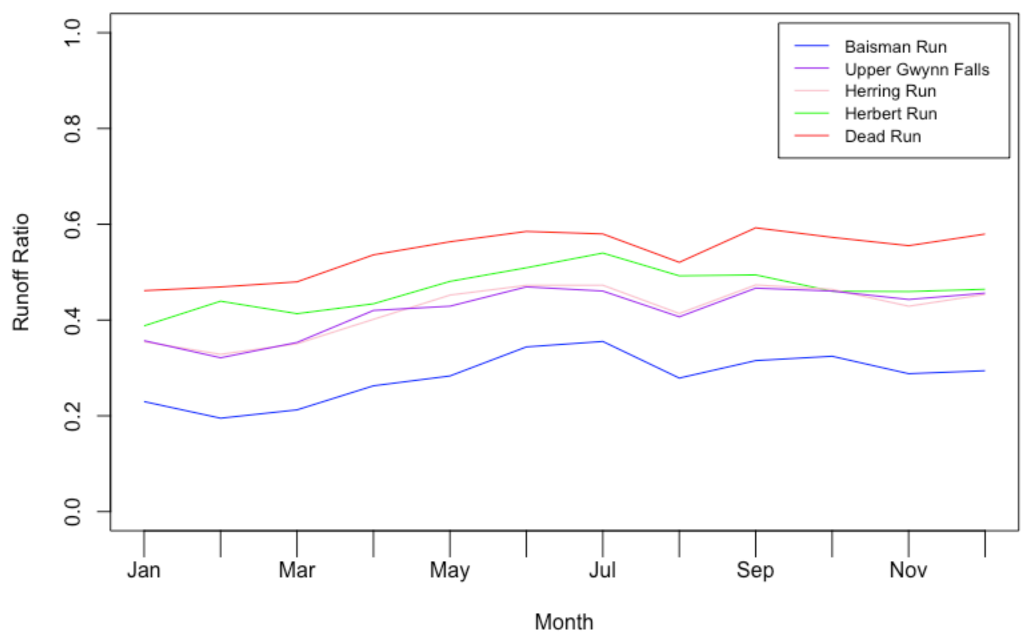

Figure 9. Average monthly runoff ratios (2000-2009) using i-Tre Hydro streamflow predictions and MET station precipitation data

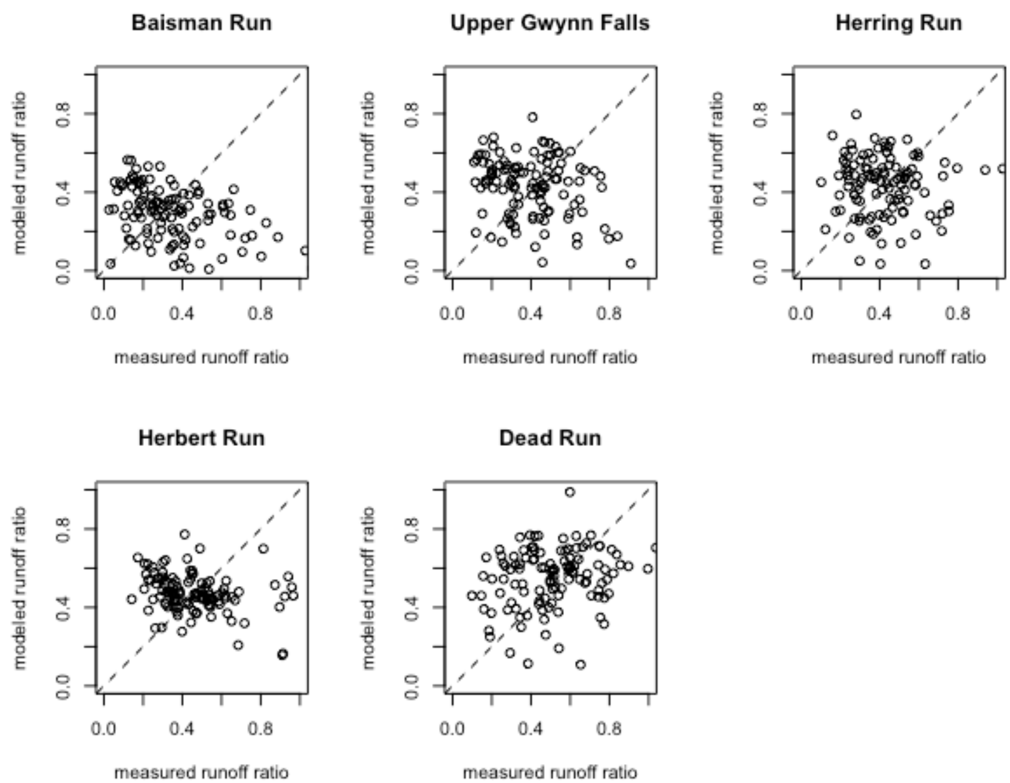

Figure 10. Runoff ratio comparison for modeled and measured runoff using BWI precipitation data

4.0 Conclusions

The greatest conclusion that can be drawn from this study is the necessity of accurate precipitation data for hydrologic modeling. The selection of the Baltimore Ecosystem Study as a second research area was made with the intent of securing data with a higher degree of resolution and accuracy, although doubts regarding this dataset led to use of the BWI Airport precipitation measurements to fill gaps and replace unusual observations. However, using both of these datasets, some conclusions can be made regarding both the effect of urbanization on runoff ratios and ET, and the ability of i-Tree Hydro to accurately model aspects of the hydrologic cycle.

Based on the difference seen between the most- and least-forested watersheds during the summer months using the measured streamflow and BWI Airport precipitation data, the hypothesis that ET rates — and the presence of trees driving that ET — can have a meaningful impact on stormwater runoff is supported. Future researchers could use a longer record of precipitation and streamflows to further identify the drivers of seasonal changes in runoff in small urban watersheds, as the 10-year record used in this study may not be large enough to represent the wide array of possible weather conditions.

In terms of answering the questions spurred on by the Bronx River watershed portion of the study, questions regarding the accuracy of input data, model calibration, and the modeling of hydrologic processes remained an issue. The results do provide partial answers to the questions regarding the ability of i-Tree Hydro to calibrate and accurately model flow series.

Observing the relative flow series predicted by i-Tree Hydro, land cover differences seem to overall be represented. However, seasonal variations in ET do not seem to be well represented for the calibrated model at these watersheds. This may be the result of i-Tree Hydro being focused on urban watersheds; the model may not adequately represent ET fluxes at forested watersheds such as Baisman Run. This is supported by the higher NSE values for the urbanized watersheds than for the forested ones. The overestimation of streamflows within Baisman Run using the model also introduced further questions regarding the model calibration routine, particularly because these same extremes were not present in the model using the BWI Airport precipitation.

Further steps could be taken to isolate the seasonal effects of ET within the i-Tree Hydro model, possibly by manually producing a precipitation and streamflow dataset that emphasizes the seasonal variation in runoff ratios, and seeing if the model is able to accurately represent this. Another option would be to identify two watersheds of similar land cover fractions, one in a region with significant seasonal ET variation (i.e. the Northeast U.S.) and one in a region with less variation (i.e. near the Equator), and use both watersheds to run the model. The two resulting outputs would be useful for isolating the seasonal ET variations within the model.

Overall, this study supports the hypothesis that ET can play a major role in the hydrologic cycle in urban watersheds, and urban trees can help to mitigate streamflow from precipitation events especially during the summer months.

Appendix

Table 5. Average monthly runoff ratios (2000-2009) using observed streamflow and adjusted NEXRAD precipitation data

Month	Baisman Run	Upper Gwynn's Falls	Herring Run	Herbert Run	Dead Run
January	0.49	0.54	0.56	0.52	0.50
February	0.86	0.72	0.74	0.77	0.74
March	0.60	0.60	0.56	0.50	0.56
April	0.43	0.53	0.48	0.41	0.38
May	0.47	0.39	0.34	0.40	0.31
June	0.33	0.46	0.39	0.30	0.31
July	0.26	0.40	0.35	0.29	0.26
August	0.24	0.31	0.31	0.26	0.26
September	0.23	0.33	0.31	0.30	0.28
October	0.38	0.39	0.39	0.35	0.42
November	0.29	0.49	0.43	0.38	0.41
December	0.36	0.65	0.52	0.47	0.47

Table 6. Average monthly runoff ratios (2000-2009) using observed streamflow and MET station precipitation data

Month	Baisman Run	Upper Gwynn's Falls	Herring Run	Herbert Run	Dead Run
January	0.50	0.49	0.51	0.52	0.51
February	0.95	0.85	0.81	0.77	0.77
March	1.01	0.92	0.79	0.72	0.77
April	0.54	0.45	0.49	0.54	0.61
May	0.49	0.34	0.37	0.40	0.44
June	0.29	0.31	0.36	0.38	0.46
July	0.21	0.21	0.34	0.34	0.36
August	0.19	0.27	0.32	0.29	0.35
September	0.25	0.40	0.37	0.44	0.46
October	0.25	0.40	0.38	0.42	0.48
November	0.29	0.42	0.43	0.47	0.56
December	0.38	0.50	0.52	0.51	0.68

Table 7. Average monthly runoff ratios (2000-2009) using i-Tree Hydro streamflow predictions and adjusted NEXRAD precipitation data

Month	Baisman Run	Upper Gwynn Falls	Herring Run	Herbert Run	Dead Run
January	0.97	0.55	0.40	0.32	0.48
February	1.59	0.66	0.43	0.33	0.52
March	1.10	0.59	0.45	0.36	0.49
April	0.47	0.59	0.51	0.44	0.51
May	0.77	0.55	0.48	0.33	0.48
June	0.65	0.58	0.53	0.41	0.50
July	0.79	0.54	0.48	0.41	0.41
August	1.02	0.55	0.42	0.44	0.45
September	1.16	0.54	0.47	0.38	0.46
October	1.02	0.61	0.46	0.45	0.57
November	0.76	0.62	0.51	0.44	0.53
December	0.63	0.66	0.57	0.49	0.59

Table 8. Average monthly runoff ratios (2000-2009) using i-Tree Hydro streamflow predictions and MET station Precipitation data

Month	Baisman Run	Upper Gwynn's Falls	Herring Run	Herbert Run	Dead Run
January	0.23	0.36	0.35	0.39	0.46
February	0.20	0.32	0.33	0.44	0.47
March	0.21	0.35	0.35	0.41	0.48
April	0.26	0.42	0.40	0.43	0.54
May	0.28	0.43	0.45	0.48	0.56
June	0.34	0.47	0.47	0.51	0.59
July	0.36	0.46	0.47	0.54	0.58
August	0.28	0.41	0.41	0.49	0.52
September	0.32	0.47	0.47	0.49	0.59
October	0.32	0.46	0.46	0.46	0.57
November	0.29	0.44	0.43	0.46	0.56
December	0.29	0.46	0.45	0.46	0.58

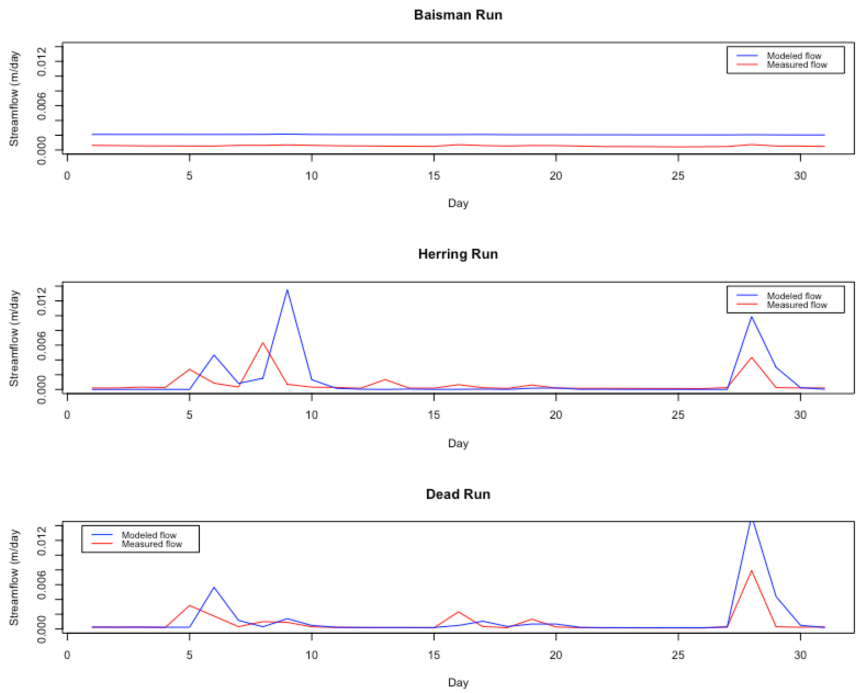

Figure 11. Streamflow Hydrograph for three target watersheds using measured and modeled streamflows for August, 2005

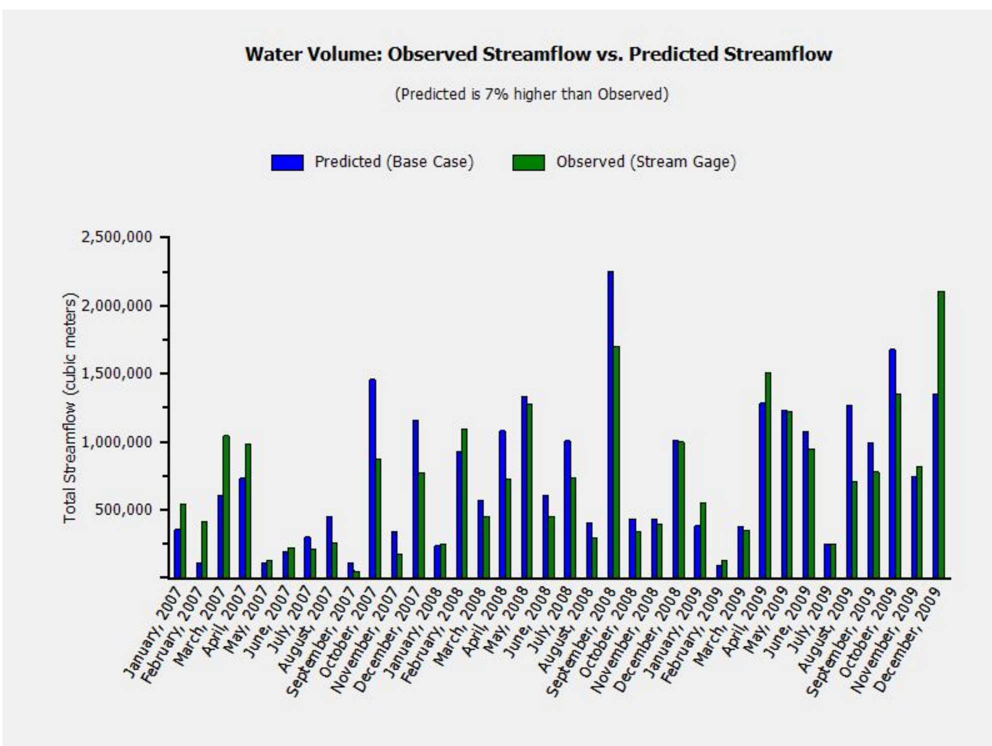

Figure 12. Monthly predicted and observed runoff for Dead Run watershed for calibration period (January 2007 - December 2009)

Table 9. Calibrated parameter set for five target watersheds (denotes calibrated parameter in i-Tree Hydro Version 6)*

Parameter	Baisman	Upper Gwynn Falls	Herring Run	Herbert Run	Dead Run
Leaf Transition Period (days)	28	28	28	28	28
Leaf On Day	113	113	113	113	113
Leaf Off Day	297	297	297	297	297
Tree Bark Area Index	1.7	1.7	1.7	1.7	1.7
Shrub Bark Area Index	0.5	0.5	0.5	0.5	0.5
Leaf storage (mm)	0.2	0.2	0.2	0.2	0.2
Pervious Depression Storage (mm)	1	1	1	1	1
Impervious Depression Storage (mm)	2.5	2.5	2.5	2.5	2.5
Scale Parameter of Power Function	2	2	2	2	2
Scale Parameter of Soil Transmissivity*	1.2	1.2	0.029398	0.024023	0.020586
Transmissivity at Saturation (m^2/h) *	84.659	0.038	0.002	0.005	0.255
Unsaturated Zone Time Delay (h)	10	10	10	10	10
Time Constant for Pervious Area flow A (h)	40	40	40	40	40
Time Constant for Pervious Area flow B (h)	40	40	40	40	40
Time Constant for DCIA flow A (h)	40	40	40	40	40
Time Constant for DCIA flow B (h)	40	40	40	40	40
Time Constant for Subsurface Flow (h)	120	120	120	120	120
Soil Macropore Percentage*	0.0000010039	0.000001	0.0000010018	0.0000010058	0.00000099
Watershed area where rainfall rate can exceed infiltration rate (%)	100	100	100	100	100

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